DESCRIPTION

HIGH-VOLTAGE INSULATION SYSTEM

The present invention relates to the field of high-voltage insulation. It relates in particular to a high-voltage insulation system for electrical insulation of components whose operating temperature is below room temperature, as claimed in the precharacterizing clause of patent claim 1, and a method for producing such a system, as claimed in the precharacterizing clause of patent claim 8.

For use in the field of electrical power supply with system voltages of up to 550 kV, a high-voltage insulation system which is suitable for low temperatures is required for electrical parts or components which are intended to be used primarily at an operating temperature below room temperature. A combination of a coolant and solid material insulation is often used for this purpose. If the envisaged operating temperatures are sufficiently low, chemical aging processes as degradation mechanisms for the solid material insulation can virtually be ruled out. On the other hand, thermal stresses are caused in the insulation material as a result of the difference between the manufacturing temperature and the operating temperature, which may lead to damage such as cracks or de-lamination when cooled down and heated up frequently. If the electrical parts or components are in direct mechanical contact with the solid material insulation, the thermal co-efficient of expansion of the insulation must, furthermore, not differ excessively from that of the component, in order to avoid stresses in the latter.

Electrical parts having components based on high-temperature superconductors, for example, cables,

transformers, current limiters and the like, are of particular interest. Liquid nitrogen (LN_2) is preferably used for cooling high-temperature superconductors to operating temperatures below 80 K.

The solid material insulation which is used is also generally intended to have a certain mechanical robustness and to be capable of acting as a support or stabilizer for, for example, components composed of ceramic high-temperature superconductor material. Insulation composed of polymer films or sulfate paper is not suitable for use in these circumstances. Insulation components which can be stressed mechanically are normally produced from glass-fiber-reinforced fiber composite materials. The latter contain a polymer matrix composed of cured epoxy resin and glass fibers or carbon fibers as the reinforcing base material. Fiber composite materials containing glass fibers have a low partial discharge inception field of ≈ 1 kV/mm at 77 K, however, and even if special vacuum-pressure impregnation methods are used for casting the resin compound, the best that can be achieved is ≈ 4 kV/mm. Accordingly, in order to avoid excessive field strengths, the insulation must not be less than a certain minimum thickness, which is not consistent with efforts to achieve compact dimensions.

Pressboards, i.e. compressed boards produced from cellulose are frequently used for insulation of transformers and are in widespread use, for example, under the name "Transformerboard". These are available in thicknesses from 0.5 mm to a few mm and, in laminated and bonded form, up to more than 100 mm. US 3,710,293 discloses an insulation system comprising layers of pressboards and sulfate or kraft paper, which are cast using a thermoplastic resin. As an alternative to this, solid material insulation impregnated with oil and composed of cellulose paper is used to form

barriers between adjacent winding layers in oil-cooled transformers. First, however, the former has to be dried by means of a complex heat-treatment and vacuum method. This is intended to prevent the cellulose material from releasing water to the oil and thus reducing its dielectric characteristics.

The object of the present invention is to provide a high-voltage insulation system for use at temperatures below room temperature and with a high partial discharge inception field, and to specify a method for producing such a system.

These objects are achieved by a high-voltage insulation system having the features in patent claim 1, and by a method having the features in patent claim 8.

The essence of the invention is to use an electrically insulating coolant in conjunction with solid material insulation in the form of a composite material, which comprises cellulose fibers impregnated with polymer resin. The increased partial discharge inception field of the polymer composite allows the high-voltage insulation system to have more compact dimensions and thus also results in cost savings.

According to a first preferred embodiment, liquid nitrogen LN_2 is used as the coolant. LN_2 is suitable for cooling high-temperature superconductors to an operating temperature of 77 K or less. In the range between room temperature and the operating temperature, the mean thermal coefficient of expansion of the cellulose polymer matrix composite is comparable to that of the high-temperature superconductor. This results in the possibility of bringing the cellulose composite and the high-temperature superconductor into direct and permanent mechanical contact without any

need to be concerned about damage induced by stresses during cooling or heating.

In order to allow the solid material insulator to provide mechanical support for the high-temperature superconductor ceramic, the cellulose material is advantageously used in the form of pressboards. In order to achieve greater thicknesses and further improve mechanical robustness, a number of thin boards, which can be formed individually, can be laminated. An intermediate layer composed of a suitable fabric absorbs excess polymer resin and prevents the formation of a pure resin layer between the pressboards.

The method according to the invention for producing a high-voltage insulation system which is suitable for low temperatures, is distinguished by the pressboards being formed in the dry state and then being impregnated, that is to say, soaked with a polymer resin. Since the process of forming the pressboards does not involve moistening them, there is also no need for the tedious drying process required for the subsequent impregnation. In consequence, there is no risk either of the formed pressboard becoming inadvertently distorted during the drying process.

According to a further embodiment, a cylindrical coil former or coil support is formed from the pressboards, and a superconducting wire is then wound on it. The coil former and winding are then jointly encapsulated with polymer resin, which results in the windings being bonded and mechanically fixed to the coil former.

Advantageous embodiments are described in the dependent patent claims.

The invention will be explained in more detail in the following text with reference to exemplary embodiments and in conjunction with the drawings, in which:

Figure 1a shows a detail of a high-voltage insulation system according to the invention,

Figure 1b shows a section through an arrangement having a conductor which is electrically insulated according to the invention,

Figure 2 shows a coil having a coil former as part of a high-voltage insulation system according to one preferred embodiment of the invention.

The reference symbols used in the drawings are summarized in the list of reference symbols. In principle, identical parts are provided with the same reference symbols.

Figure 1a shows a high-voltage insulation system according to the invention together with a conductor 1 which is at a high electrical potential. Conductor 1 is part of an electrical component which, in order to operate in its intended manner, must be cooled to an operating temperature which is below ambient or room temperature (20-25°C). The high-voltage insulation system comprises a solid material insulator 2 and a fluid, that is to say liquid or gaseous coolant 3. The solid material insulator 2 comprises a base fabric 20 and a polymer matrix 21. The matrix systems are preferably three-dimensionally crosslinked thermosetting plastics and are based, for example, on cured epoxy, silicon or polyester resins. According to the invention, the base fabric 20 is composed of cellulose fibers (processed cellulose).

Figure 1b shows an arrangement having a conductor 1 as a part of an electrical component which is to be cooled and is connected via supply lines 4 to a power supply system, which is not illustrated. The conductor 1 is surrounded by solid material insulation 2 according to the invention, and is immersed in a cooling liquid 3. The cooling liquid 3 is contained in a thermally insulating cooling container 5.

In the prior art, glass fibers are used because of the mechanical characteristics which can be achieved, and they are impregnated with a polymer resin. The reason for the disappointing partial discharge inception field of less than 4 kV/mm mentioned initially for impregnated glass fibers is the fact that the glass fibers need to be coated, and this prevents the fibers from being completely wetted with resin. This results in microscopically small cavities on the fibers in which partial discharges take place, and this in turn leads to accelerated aging of the glass fiber insulation. In contrast, partial discharge inception fields of up to 10 kV/mm can be achieved at a temperature of 77 K using cellulose impregnated with polymer resin, since the cellulose fibers can be impregnated better and no cavities are formed.

The conductor 1 is, for example, a high-temperature superconductor and, as such, is part of a component used for electrical power transmission (transmission cable, transformer or current limiter). The planar conductor geometry shown in Figure 1 is in no way exclusive, and the conductor 1 may also be suitably curved or be in the form of a wire, possibly in conjunction with a normally conductive matrix. Furthermore, the use of substrates or normally conductive bypass layers is feasible. The critical temperature of known high-temperature superconductor materials is more than 80 K, so that the use of liquid

nitrogen LN_2 as the coolant, whose boiling point under normal pressure is 77 K, allows high-temperature superconductors such as this to be used.

The thermal coefficient of expansion of a ceramic superconductor is typically about 10×10^{-6}/K, and the coefficient of expansion along the plane of a cellulose fabric impregnated with polymer resin is in the range $6-13 \times 10^{-6}$/K. There is thus so little difference between the thermal coefficients of expansion that the cellulose composite and the high-temperature superconductor contract to the same extent during cooling to the operating temperature. Thus, if they have both been bonded in advance at ambient temperature, for example by means of the said polymer resin to form a mechanical composite, no thermo-mechanical stresses occur.

Cellulose is available, inter alia, pressed in the form of pressboards, with a density of ≈ 1.2 g/cm^3. Boards such as these can also be impregnated with low-viscosity polymer resins using appropriate processes. For this purpose, the boards must be thoroughly dried in advance. Such encapsulated boards may provide a supporting function and, thanks to the similar thermal coefficients of expansion, can stabilize superconductors adjacent to them.

Individual thin boards can be formed to a certain extent, with this process normally being carried out in the moist state. A problem in this case is that the geometry of the formed plate changes once again during the subsequent drying process, that is to say a certain amount of shape instability occurs. If dry forming is used, the minimum radius of curvature cannot be reduced indefinitely, and the minimum radius of curvature which can be achieved for a board thickness of 1 mm is 15 cm.

Formed or planar individual boards can be joined together, and then impregnated, to form laminates.

For this purpose, it is advantageous to provide an intermediate layer between the individual boards, since, otherwise, excess resin can accumulate as a thin, pure resin layer with a thickness of < 50 µm between the boards. On cooling, this leads to a tendency to de-lamination of the laminate. A fabric composed of cotton, nylon fibers or polyethylene fibers is suitable, for example, as the material for the intermediate layer.

Figure 2 shows, schematically, a superconducting coil having a hollow-cylindrical coil former 6, composed of a composite having two layers 60, 61 which have been formed individually to create tubes and are separated by an intermediate layer 62. A superconducting wire 1′ is wound on the coil former 6. The interior of the coil former 6 and the external area surrounding the coil are filled with a coolant, which is not illustrated. During production of the coil, it is advantageous not to carry out the impregnation process, that is to say the encapsulation of the coil, until the wire 1′ has been wound onto it, since this also results in the wire 1′ being fixed on the coil former 6.

Since one unavoidable problem in high-voltage components is the major increase in the electrical field at edges, apertures and the like, it is advantageous to provide the insulation system and, in particular, the solid material insulator, with certain field-controlling or field-grading characteristics. To this end, a material having a high dielectric constant, for example, carbon black, is added in powder form to the polymer resin, or is provided in fabric form as part of the intermediate layer. This gives the composite semiconductive characteristics. An aluminum

foil can likewise be used as part of the intermediate layer for geometric field grading.

If additional mechanical reinforcement is desired, further glass fibers can be used, once again either in the polymer matrix or as a glass fiber mat in the intermediate layer. This is done, of course, only where there are no high electrical fields and there is no need to be concerned about partial discharges.

LIST OF REFERENCE SYMBOLS

1,1'	Conductor, winding
2	Solid material insulator
20	Base fabric
21	Matrix
3	Coolant
4	Supply lines
5	Coolant container
6	Coil former
60, 61	Rolled pressboards
62	Intermediate layer